INTERACTION OF RADIATION WITH MATTER.

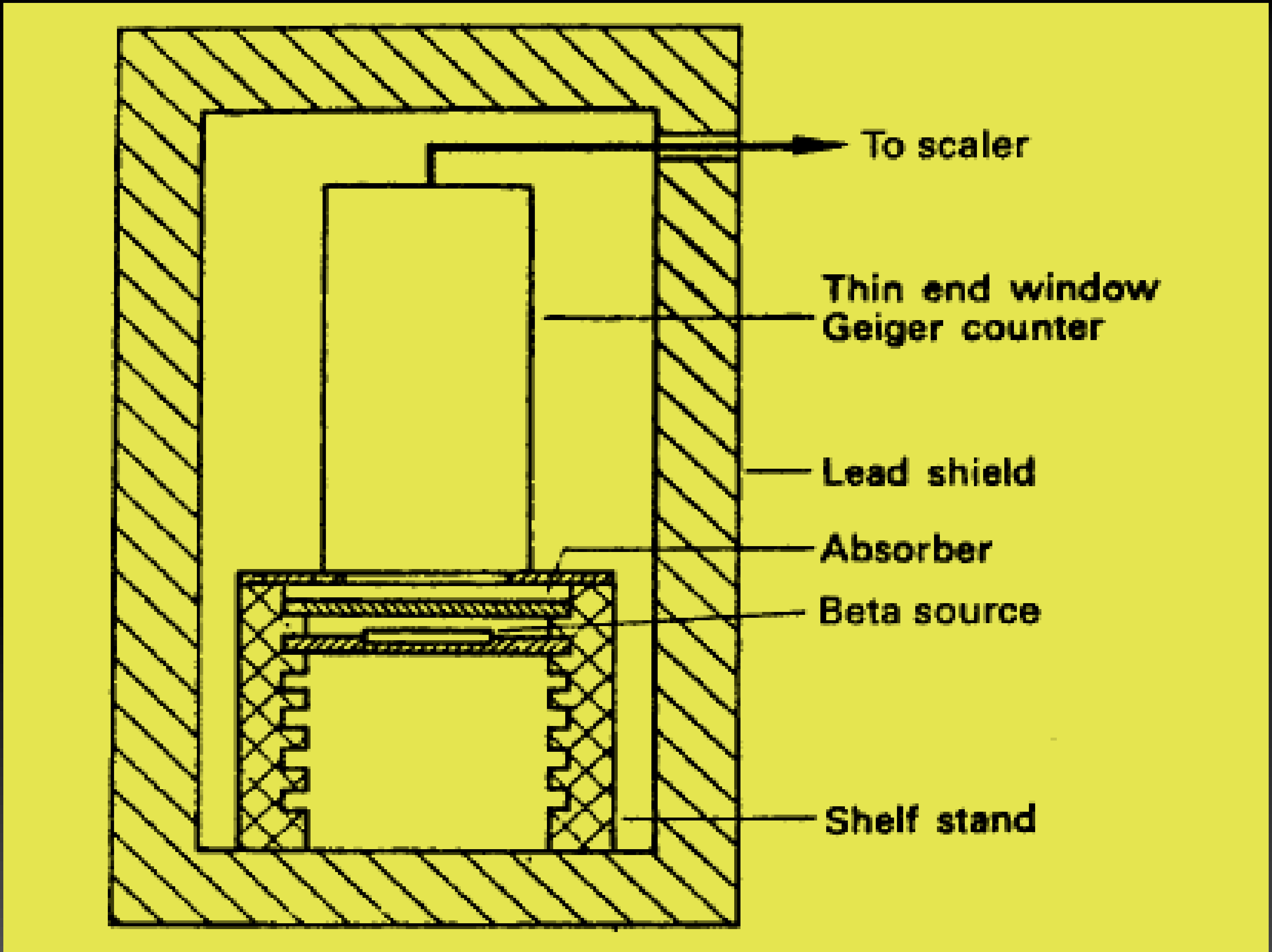
In order for health physicists to understand the physical basis for radiation dosimetry and the theory of radiation shielding, they must understand the mechanisms by which the various radiations interact with matter. In most instances, these interactions involve a transfer of energy from the radiation to the matter with which it interacts. Matter consists of atomic nuclei and extranuclear electrons. Radiation may interact with either or both of these constituents of matter.

The probability of occurrence of any particular category of interaction, and hence the penetrating power of the several radiations, depends on the type and energy of the radiation as well as on the nature of the absorbing medium.

BETA PARTICLES (BETA RAYS)

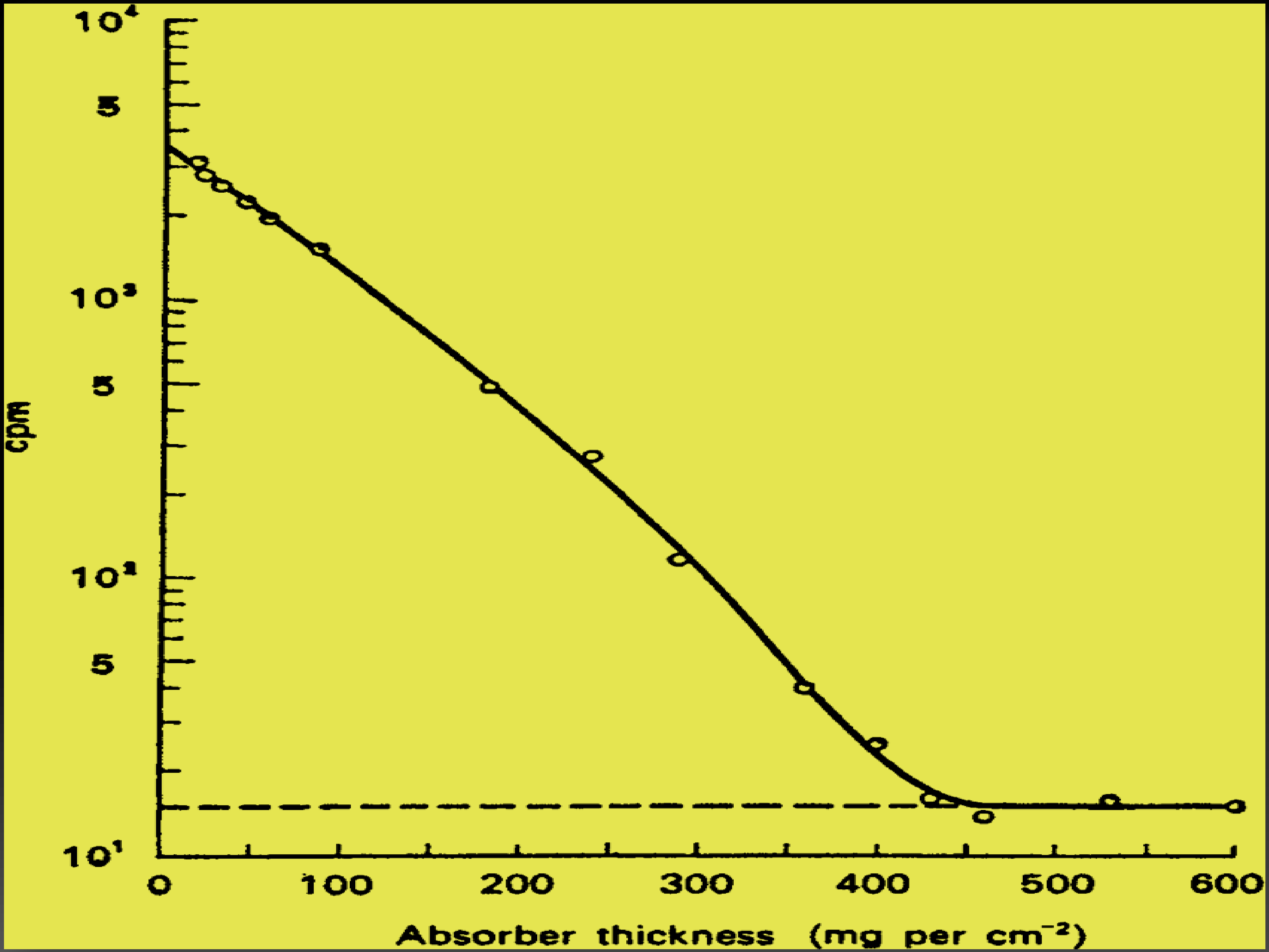
The attenuation of beta particles used by any given absorber may be measured by interposing successively thicker absorbers between a beta source and a suitable beta detector, such as a Geiger–Muller counter, and counting the beta particles that penetrate the absorbers .When this is done with a pure beta emitter, it is found that the beta-particle counting rate decreases rapidly at first, and then, as the absorber thickness increases, it decreases slowly.

Figure (1-1)


To scaler
Thin end window
Geiger counter
Lead shield
Absorber
Beta source
Shelf stand

Eventually, a thickness of absorber is reached that stops all the beta particles; the Geiger counter then registers only background counts due to environmental radiation. If semilog paper is used to plot the data and the counting rate is plotted on the logarithmic axis while absorber thickness is plotted on the linear axis, the data approximate a straight line, as shown in Figure

Figure (1-2)

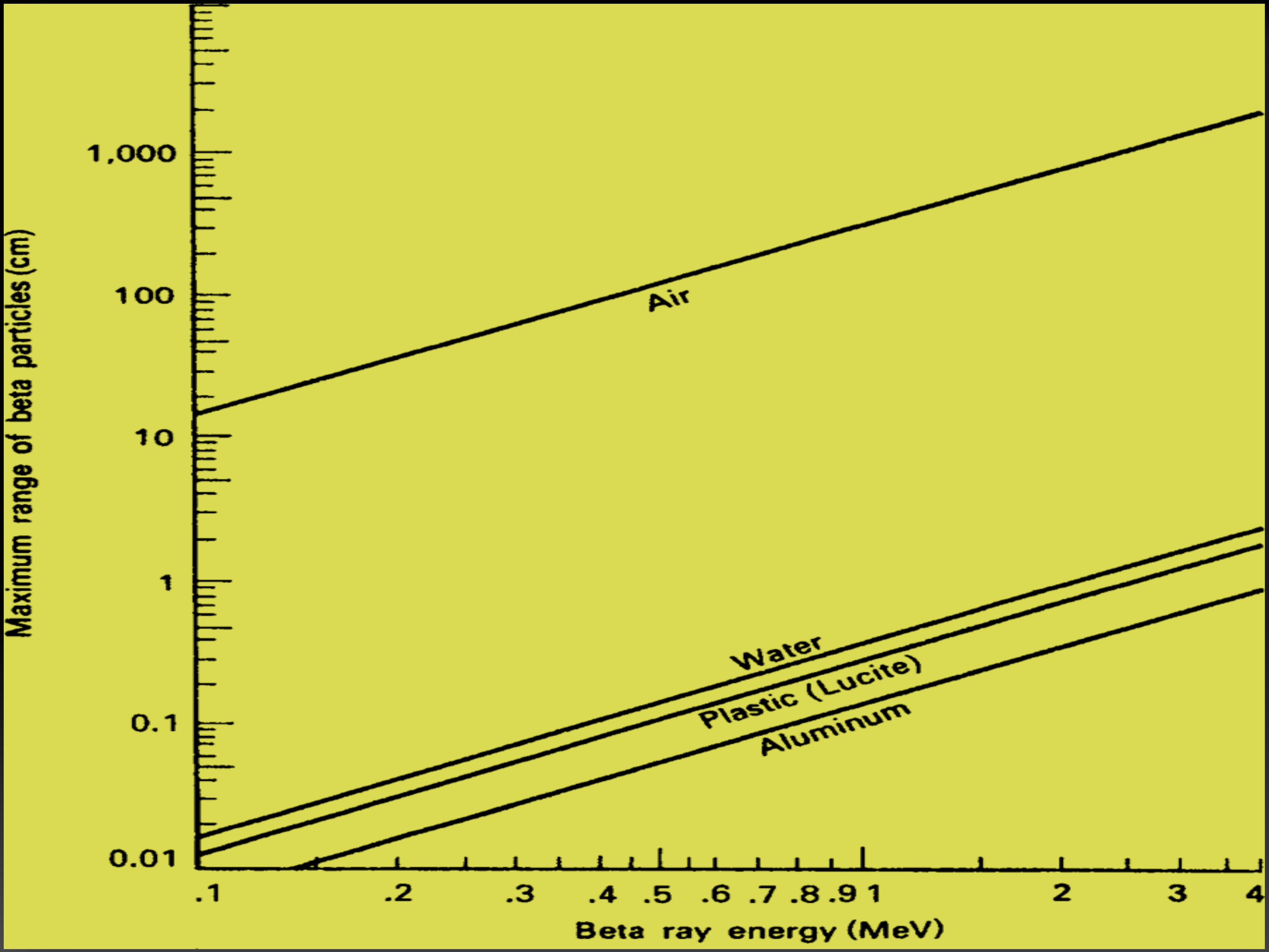


10^4
5
10^3
5
10^2
5
10^1
cpm
0
100
200
300
400
500
600
Absorber thickness (mg per cm^{-2})

The end point in the absorption curve, where no further decrease in the counting rate is observed, is called the *range of the beta in the material of which the absorbers are* made. A useful relationship is that the absorber half thickness (that thickness of absorber which stops one-half of the β particles) is about (1/8) the range of the β. Since the maximum β energies for the various isotopes are known, by measuring the β ranges in different absorbers, the systematic relationship between range and energy shown in Figure is established.

Inspection of Figure shows that the required thickness of absorber for any given β energy decreases as the density of the absorber increases. Analysis of the data show that the ability to absorb energy from βs depends mainly on the number of absorbing electrons in the path of the β areal density (electrons/cm^2) of electrons in the absorber, and, to a much lesser degree, on the atomic number(Z) of the absorber. For practical purposes, therefore, in the calculation of shielding thickness against β particles, the effect of is neglected.

Figure (1-3)



Maximum range of beta particles (cm)
1,000
100
10
1
0.1
0.01
Air
Water
Plastic (Lucite)
Aluminum
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
2
3
4
Beta ray energy (MeV)

Areal density of electrons is approximately proportional to the product of the density of the absorber material and the linear thickness of the absorber, called the *density thickness*. t_d is defined as $t_d\ g/cm^2 = \rho\ g/cm^3 \times t_l\ cm.$ **(1.1)**

Use of the density thickness unit, such as g/cm^2 or mg/cm^2 for absorber materials, makes it possible to specify such absorbers independently of the absorber material. For example, the density aluminum is 2.7 g/cm^3. From Eq. (1.1), a 1-cm-thick sheet of aluminum, therefore has a density

$$t_d = 2.7\,\frac{\text{g}}{\text{cm}^3} \times 1\,\text{cm} = 2.7\,\frac{\text{g}}{\text{cm}^2}.$$

If a sheet of Plexiglas whose density is 1.18 g/cm^3 is to have a β absorbing quality nearly equal to that of the 1-cm-thick sheet of aluminum—that 2.7 g/cm^2—its linear thickness is found, from Eq. (1.1), to be

$$t_l = t_d\,(g/cm^2)/\,\rho(g/cm^3) = 2.7\,/\,1.18 = 2.29\text{ cm}$$

The quantitative relationship between beta energy and range is given by the following experimentally determined empirical equations:

$$E = 1.92\,R^{0.725} \qquad R \le 0.3\,\mathrm{g/cm^2}$$

$$R = 0.407\,E^{1.38} \qquad E \le 0.8\,\mathrm{MeV}$$

$$E = 1.85\,R + 0.245 \qquad R \ge 0.3\,\mathrm{g/cm^2}$$

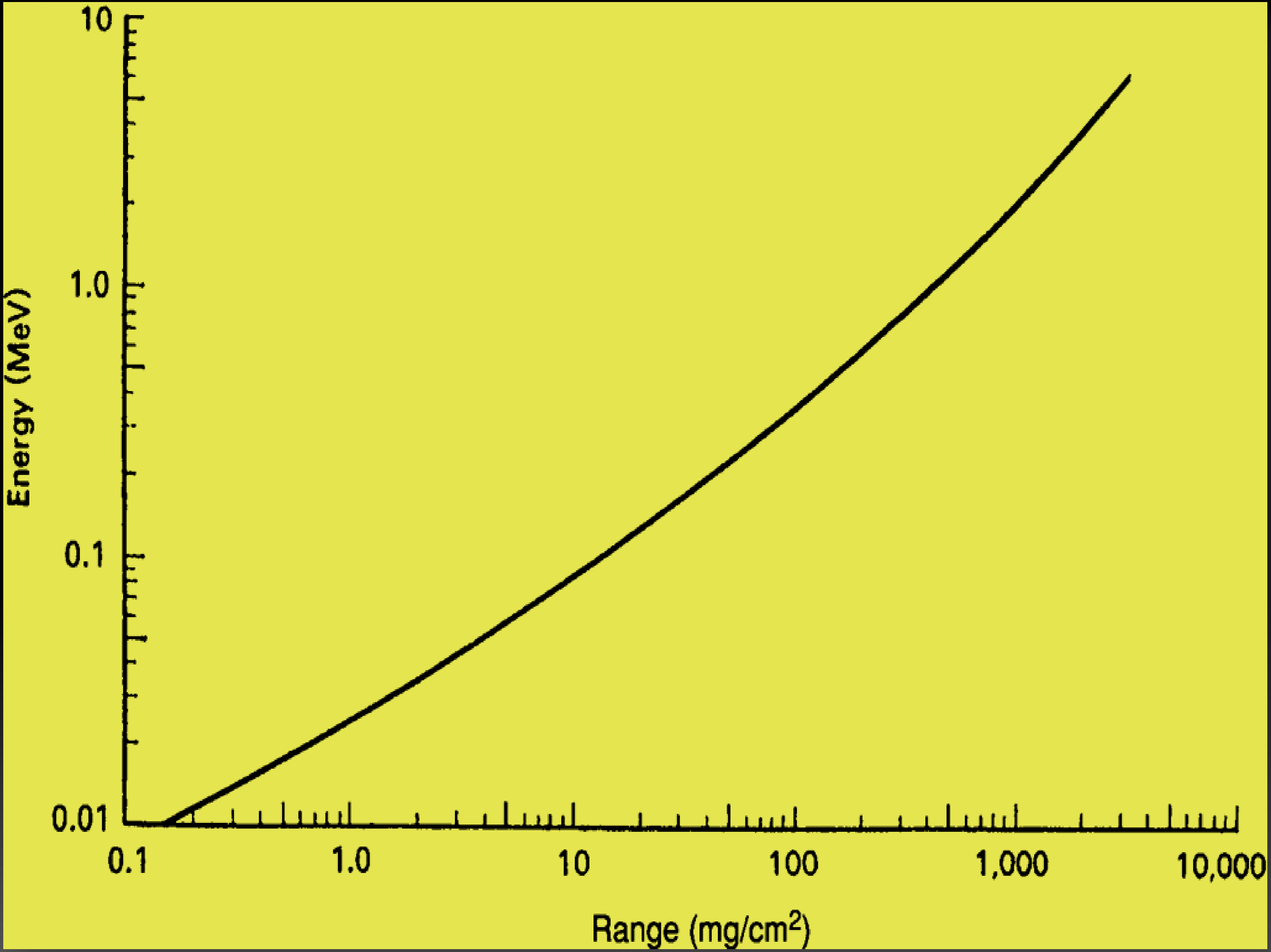
$$R = 0.542\,E - 0.133 \qquad E \ge 0.8\,\mathrm{MeV}$$

where

R = range, $\mathrm{g/cm^2}$ and
E = maximum beta energy, MeV.

An experimentally determined curve of beta range (in units of density thickness expressed as $\mathrm{mg/cm^2}$) versus energy is given in Figure

Figure (1-4)



Example 1.1

What must be the minimum thickness of a shield made of (a) Plexiglas and
(b) aluminum in order that no β particles from a ^{90}Sr source pass through?
^{90}Sr emits a 0.54-MeV β particle. However, its daughter, ^{90}Y, emits a β particle whose maximum energy is 2.27 MeV. Since ^{90}Y β particles always accompany ^{90}Sr β particles, the shield must be thick enough to stop these more energetic
βs . If we substitute 2.27 MeV for *E in last Eq*.
The range of βs

$$R = (0.542 \times 2.27) - 0.133 = 1.1 \, \mathrm{g/cm^2}.$$

Alternatively, from Fig (1-4), the range of a 2.27-MeV beta particle is found to be1.1 g/cm^2. The density of Plexiglas is 1.18 g/cm^3. From Eq. (1.1), the required

Thickness is found to be

$$t_1 = \frac{t_d}{\rho} = \frac{1.1\,\mathrm{g/cm^2}}{1.18\,\mathrm{g/cm^3}} = 0.932\,\mathrm{cm}.$$

Plexiglas may suffer radiation damage and crack if exposed to very intense radiation for a long period of time. Under these conditions, aluminum is a better choice for a shield. Since the density of aluminum is 2.7 g/cm^3, the required thickness of aluminum is found to be 0.41 cm (= 1.1/2.7)

The range energy relationship is often used by the health physicist as an aid in identifying an unknown ***β*** emitting containment. This is done by measuring the range of the beta radiation, then finding energy of ***β*** ray, then looking up in table of isotopes the isotope that emits a ***β*** particle of that energy.

EXAMPLE 1.2

Using the counting setup shown in Fig.1-5, *β* radiation from an unidentified radionuclide was stopped by a 0.111-mm-thick aluminum absorber. No measurable decrease of the radioactivity in the sample was observed during a period of 1 month and no other radiation was emitted from the sample.

(a) What was the energy of the beta particle?

(b) What is the isotope?

Solution

The total range of the beta particle is given as:

Range = 1.7 mgcm^2 mica + 1 cm air + 0.*111mmAl*.

These different absorbing media may be added together if their thicknesses are expressed as density thickness. The density of air is 1.293 mg/cm^3 at standard temperature and pressure (STP). With Eq. (1.1), the density thicknesses of the air

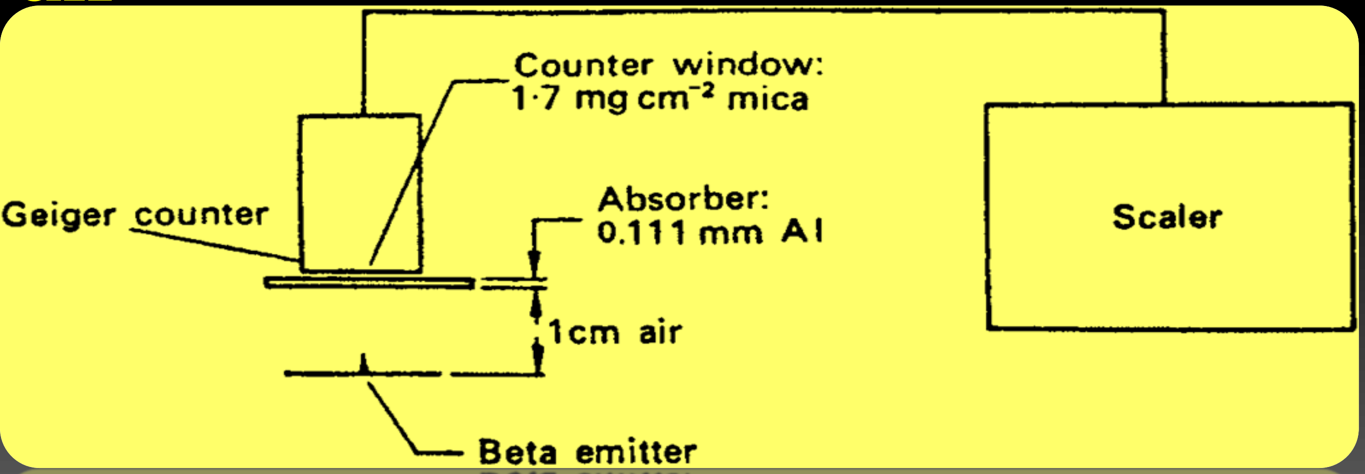


Figure (1-5)

and aluminum are computed and the range of the unknown beta particle is found to be Range =1*.7 mg/cm^2 +1.29 mg/cm^2 + 30 mg/cm^2 = 32.99 mg/cm^2*

In Figure , the energy corresponding to this range is seen to be about 0.17 MeV.

The unknown radionuclide is therefore likely to be ^{14}C, a pure beta emitter whose maximum beta energy is 0.155 MeV and whose half-life is about 5700 years.

Mechanisms of Energy Loss

Ionization and Excitation

Interaction between the electric fields of a *β* particle and the orbital e^- of the absorbing medium leads to electronic excitation and ionization.

The e^- is held in the atom by electrical forces, and energy is lost by the *β* particle in overcoming these forces. The “collision” between a *β* particle and an e^- occurs without the two particles coming into actual contact—as is also the case of the collision between like poles of two magnets. The energy lost by the *β* particle depends on its distance of approach to the e^- and on its kinetic energy.

If *φ is the ionization potential* of the absorbing medium and *E_t is the energy lost by the β particle during the* collision, the kinetic energy of the ejected e^- *E_k is :* $E_k = E_t - \varphi.$ *(1.6)*

In some ionizing collisions, only one ion pair is produced.In other cases, the ejected e^- may have sufficient K.E to produce a small cluster of several ionizations; and in a small proportion of the collisions, the ejected e^- may receive a considerable amount of energy enough to cause it to travel a long distance and to leave a trail of ionizations.

Such an e^-, whose kinetic energy may be on the order of 1000 eV, is called a *delta ray*. *β* particles have the same mass as orbital electrons and hence are easily deflected during collisions. For this reason, *β* particles follow tortuous paths as they pass through absorbing media

Specific Ionization

The linear rate of energy loss of a ***β*** particle due to ionization and excitation, which is an important parameter in health physics instrument design and in the biological effects of radiation, is usually expressed by the specific ionization.

Specific ionization is the number of ion pairs formed per unit distance travelled by the beta particle. Generally, the specific ionization is relatively high for low energy betas; it decreases rapidly as the beta particle energy increases, until a broad minimum is reached around 1MeV. Further increase in beta energy results in slowly increasing specification, as shown in Fig (1-6)

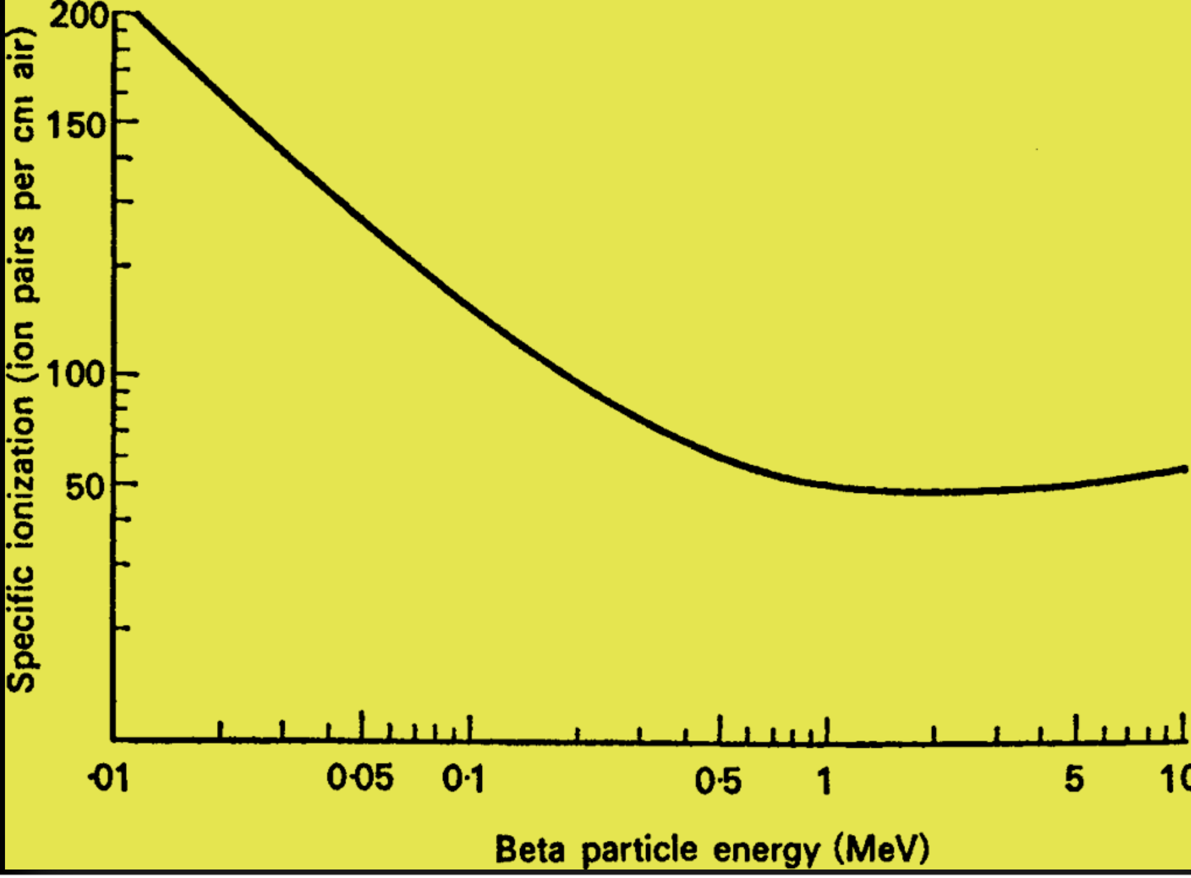


Figure (1-6)

$$\frac{dE}{dx} = \frac{2\pi q^4}{E_m \beta^2} \frac{NZ * (3 * 10^9)^4}{(1.6 * 10^{-6})^2} \left[ln \left[\frac{E_m E \beta^2}{I^2(1-\beta^2)} \right] - \beta^2 \right] \quad \frac{MeV}{cm} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1\text{-}6)$$

Where q = charge of the electron, 1.6 x 10^{-19}C,

N = number of absorber atoms per cm^3,
Z = atomic number of the absorber,
NZ =number of absorber electrons per cm^3
= 3.88x10^{20} for air at 0^0C and 76 cmHg,
E_m = energy equivalent of electron mass, 0.51MeV,
E = kinetic energy of the beta particle, MeV,
β= v/c,
I = mean ionization and excitation potential of absorbing atoms, MeV,
I = 8.6 x 10^{-5} for air, for other substances,
I = 1.35 x 10^{-5}z.

If the mean energy expended in the creation of an ion pair, ***w***, is known, then the specific ionization may be calculated from the equation below:

$$S.I. = \frac{dE/dx \ \ eV/cm}{w \ \ eV/ip}$$

(1-7)

Table(1-5). Average energy lost by β-particle in the production of an ion pair.

GAS	IONIZATION POTENTIAL (eV)	MEAN ENERGY EXPENDITURE PER ION PAIR (eV)
H_2	13.6	36.6
He	24.5	41.5
N_2	14.5	34.6
O_2	13.6	30.8
Ne	21.5	36.2
A	15.7	26.2
Kr	14.0	24.3
Xe	12.1	21.9
Air		33.7
CO_2	14.4	32.9
CH_4	14.5	27.3
C_2H_2	11.6	25.7
C_2H_4	12.2	26.3
C_2H_6	12.8	24.6

Example 1-3

What is the specific ionization resulting from the passage of a 0.1MeV beta particle through standard air?

β^2 is determined using equation:

$$E_k = m_0 c^2 \left[\frac{1}{\sqrt{(1-\beta^2)}} - 1 \right]$$

$$0.1 = 0.51 \left(\frac{1}{\sqrt{(1-\beta^2)}} - 1 \right),$$

$$\beta^2 = 0.3010$$

Substituting the respectively values into equation (1-6), we have

$$\frac{dE}{dx} = \frac{2\pi(1.6*10^{-19})^4 * 3.88*10^{20} * (3*10^9)^4}{0.51*0.3010*(1.6*10^{-6})^2} * [ln[\frac{0.51*.1*.0325}{(8.6*10^{-5})^2(1-0.3010)}] - 0.3010] \ \frac{MeV}{cm}$$

$$\frac{\text{dE}}{dx} = 4.75 * 10^{-3} MeV/cm$$

For air, ***w*** = 34eV/ip. The specific ionization, therefore, from equation (1-7), is:

$$S.I = \frac{4750\ eV/cm}{34\ eV/ip} = 140ip/cm$$

Very often, the unit of length used in expressing rate of energy loss is density thickness, that is, in units of MeV/g cm^2. This is called the mass stopping power, and is defined by the equation:

$$S = \frac{dE/dx}{\rho} \qquad \text{.................(1-8)}$$

Since the density of standard air is 1.293×10^{3} g/cm^{3}, the mass rate of energy loss, or the mass stopping power, in Example 1-3 is:

$$S = \frac{4.75 * \frac{10^{-3} MeV}{cm}}{1.293 * \frac{10^{-3} g}{cm}} = 3.67 \; \frac{Mev}{\frac{g}{cm^2}}$$

Linear energy transfer. The term specific ionization is used when attention is forced on the energy lost by the relation. When attenuation is focused on the absorbing medium, as is the case in radiobiology and radiation effects, we are interested in the linear rate of energy absorption by the absorbing medium as the ionizing particle traverses the medium. As a measure of the rate of energy absorption, we use the linear energy transfer, abbreviated LET, which is defined by the equation:

$$LET = \frac{dE_L}{dl} \quad ......(1\text{-}9)$$

Where dE_L is the average energy locally imparted to the absorbing medium by a charged particle of specified energy in traversing a distance of dl. in health physics and radiobiology, LET is usually expressed in units of KeV per micron. As used in the definition above, the term “locally imparted” may refer either to a maximum distance from the track of the ionizing particle or to a maximum value of discrete energy loss by the particle beyond which losses are no longer considered local.

In either case, LET refers to energy imparted within a limited volume of absorber.

Relative mass stopping power.

The relative mass stopping power is used to compare quantitatively the energy absorptive power of different media. It will be shown later that the mass stopping power of different absorbers relative to that of air is important in the practice of health physics. Relative mass stopping power is defined by Eq.(1-10):

$$\rho_m = \frac{S_{medium}}{S_{air}}$$

Example 4

What is the relative (to air) mass stopping power of graphite, density = 2.25g/cm^3, for a 0.1MeV beta particles?

The mass rate of energy loss in graphite is found by substituting the appropriate values into equations (1-6) and (1-8):

$$NZ = \frac{6.03 * 10^{23} atoms/mole * 2.25 g/cm^3 * 6 electrons/atom}{12 g/mole}$$

$NZ = 6.77 \times 10^{23}$ electrons/cm^3

$I = 1.35 \times 10^{-5} \times 6 = 8.1 \times 10^{-5}$,

Then calculate (dE/dx) and the stopping power

$$S_{graphite} = 3.85 \frac{MeV}{\frac{g}{cm^2}}$$

For air, the mass stopping power is 3.67MeV/g/cm^2. From equation (1-10), the relative mass stopping power of graphite for a 0.1MeV electron is:

$$\rho_m = \frac{3.85}{3.67} = 1.05$$

Bremsstrahlung

Bremsstrahlung, which is the German word meaning *braking radiation, consists of* X-rays that are produced when high-velocity charged particles undergo a rapid change in velocity, that is, when they are very rapidly accelerated. Since velocity is a vector quantity that includes both speed and direction, a change in direction, even if the speed should remain unchanged, is a change in velocity.

When a beta particle or an electron passes close to a nucleus, the strong attractive coulomb force causes the beta particle to deviate sharply from its original path. This change in

direction is a radial acceleration and the beta particle, in accordance with Maxwell’s classical theory, loses energy by electromagnetic radiation at a rate proportional to the square of the acceleration. (Radiation emitted by electrons that are undergoing radial acceleration when caused to travel in a circular path by a magnetic field

in an accelerator is called *synchrotron radiation.) Electrons or betas are decelerated* at various rates in their interaction with matter. Bremsstrahlung photons (x-rays), therefore, have a continuous energy distribution that ranges downward from a theoretical maximum equal to the kinetic energy of the most energetic beta particle.The energy distribution of the bremsstrahlung photons from a beta source is very heavily skewed toward the low energy relative to the maximum energy of the betas,as shown in Table 1-2.

Table (1-2)

X-RAY ENERGY INTERVALS IN FRACTIONS OF $E_m(\beta)$	% TOTAL PHOTON INTENSITY IN ENERGY INTERVAL
0.0–0.1	43.5
0.1–0.2	25.8
0.2–0.3	15.2
0.3–0.4	8.3
0.4–0.5	4.3
0.5–0.6	2.0
0.6–0.7	0.7
0.7–0.8	0.2
0.8–0.9	0.03
0.9–1.0	<0.01

This occurs for two reasons: First, the proportion of betas near the maximum energy is very small, that is, most of the betas are found in the lower half of the beta spectrum (Fig. 1-7), and second, most of the betas are decelerated by a series of collisions in which small amounts of energy are lost, rather than in oneor two large energy-loss collisions before being stopped.

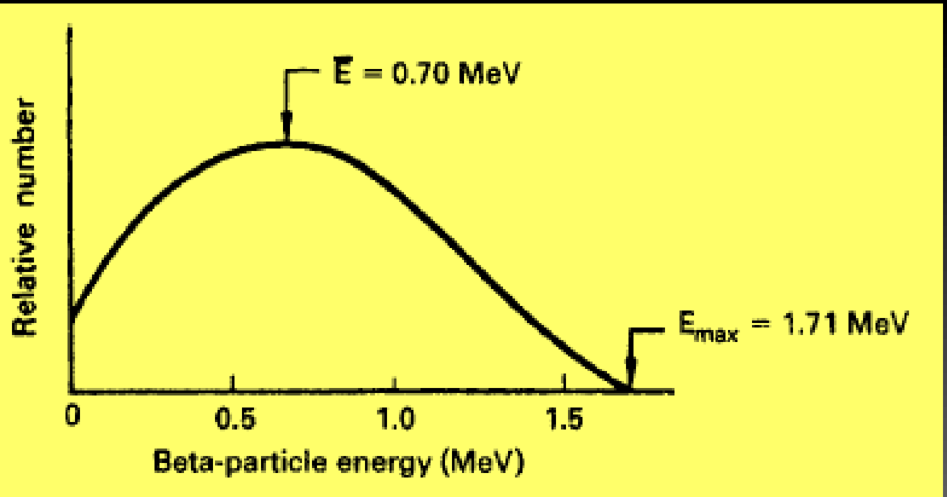


Figure (1-7)

β-spectrum of ^{32}P

It is important for users of radionuclides to know that bremsstrahlung X-rays are not a property of beta-emitting isotopes and hence are not shown in decay schemes.The X-rays are a result of the interaction of the betas with surrounding matter, such as its container or a shield. For example, the bremsstrahlung dose rate at a distance of 10 cm from an aqueous solution of 4000 MBq (~100 mCi) ^{32}P in a 25-mL volumetric flask is about 0.03 mGy/h (3 mrad/h); for 4×10^9 Bq (~100 mCi) ^{90}Sr in a brass container,

the bremsstrahlung dose rate is about 1 mGy/h (~100 mrad/h at a distance of 10 cm. (The mGy and the mrad will be formally introduced in the next chapter. At this point it is sufficient to radiation absorbed dose.) know that they are units for measuring

The likelihood of bremsstrahlung production increasesmwith increasing beta energy and with increasing atomic number of the absorber (Eq. [1.11]). Beta shields are therefore made with materials of the minimum Practicable atomic number.

$$f_\beta = 3.5 \times 10^{-4} \, Z E_{\mathrm{m}},$$

where

f_β = the fraction of the incident beta energy converted into photons,

Z = atomic number of the absorber, and

E_m = maximum energy of the beta particle (MeV).

EXAMPLE

A very small source (physically) of 3.7×10^{10}Bq (1 Ci) of ^{32}P is inside a lead shield just thick enough to prevent any beta particles from emerging. What is the bremsstrahlung energy flux at a distance of 10 cm from the source (neglect attenuation of the bremsstrahlung by the beta shield)?

Since *Z for lead is 82 and the maximum energy of the ^{32}P beta particle is 1.71 MeV*,

the fraction of the beta energy converted into photons (x-rays),

$$f = 3.5 \times 10^{-4} \times 82 \times 1.71 = 0.049.$$

Since the average beta-particle energy is about one-third of the maximum energy, the energy E_β *carried by the beta particles from the 1-Ci source that is incident on* the shield is

$$E_\beta \,(\mathrm{MeV/s}) = \frac{1}{3}\frac{E_{\max}\mathrm{MeV}}{\beta} \times 3.7 \times 10^{10}\,\frac{\beta}{\mathrm{s}}.$$

For health physics purposes, it is assumed that all the bremsstrahlung photons are of the beta particle's maximum energy, E_{max}. *The photon flux* φ *of bremsstrahlung* photons at a distance *r cm from a point source of beta particles whose activity is* 3.7×10^{10} Bq (1 Ci) is therefore given as

$$\phi = \frac{f\,E_\beta}{4\pi\,r^2\,E_{\max}}$$

Equation(1-12)

$$= \frac{0.049 \times \frac{1}{3} \times 1.71\,\frac{\text{MeV}}{\beta} \times 3.7 \times 10^{10}\,\frac{\beta}{\text{s}}}{4\pi \times (10\text{ cm})^2 \times 1.71\text{ MeV/photon}} = 4.8 \times 10^5\,\frac{\text{photons/s}}{\text{cm}^2}.$$

X-ray Production

When a beam of monoenergetic electrons that had been accelerated across a high potential difference is abruptly decelerated by stopping the electron beam (as in the case of an X-ray tube, a cathode ray tube, or a microwave generator), a small fraction of the energy in the electron beam (Eq. [1.13]) is converted into X-rays.

$$f_e = 1 \times 10^{-3} \times ZE \qquad (1\text{-}13)$$

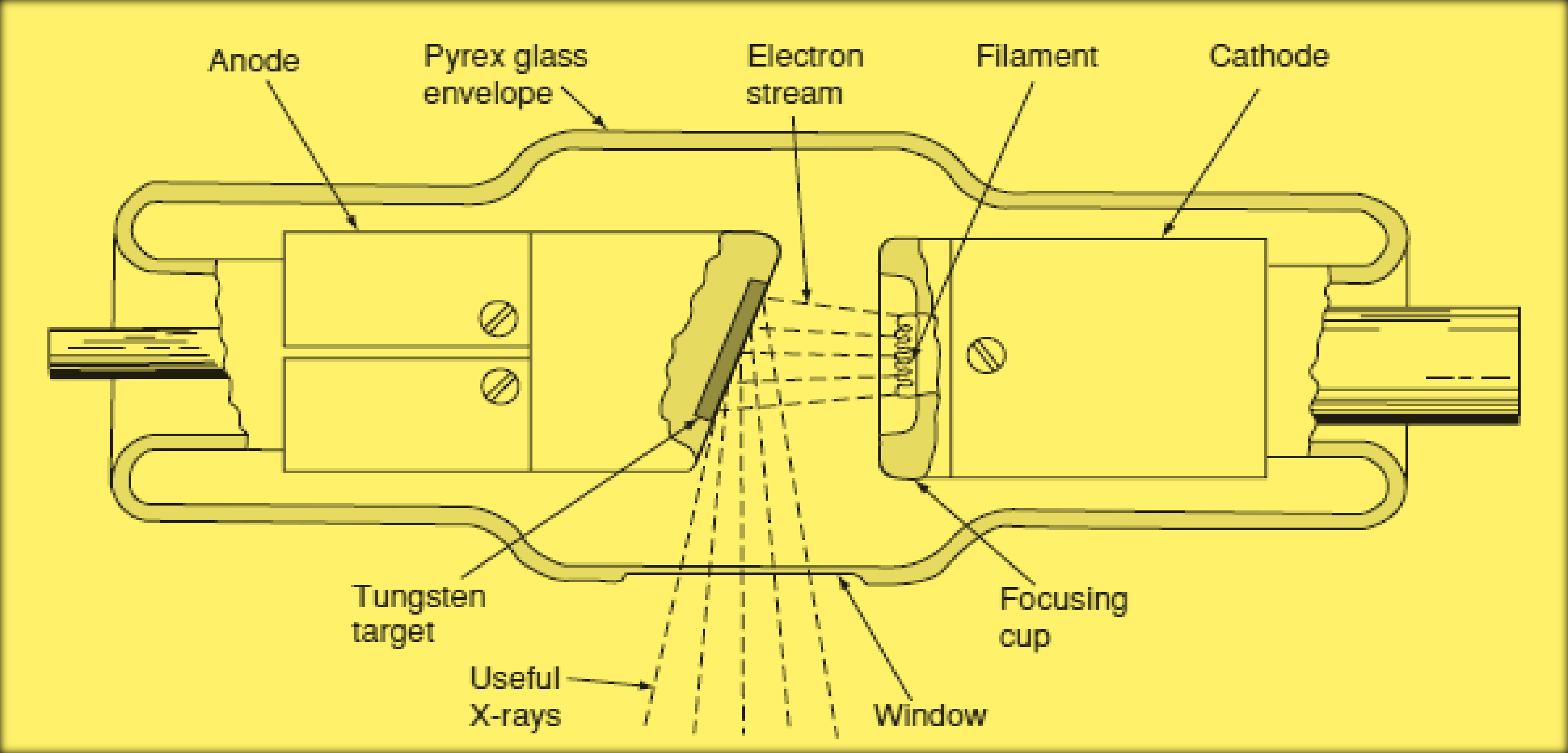
where

fe = fraction of the energy in the electron beam that is converted into X-rays,

Z = atomic number of the target in the X-ray tube or whatever the electron beam strikes in any other device, and

E = voltage across the X-ray tube or other device (mega volts, MV). The numerical value of the voltage *E is equal to the kinetic energy of the* electron, expressed in eV, as it strikes the target.

Thus, an electron that has been accelerated across a voltage of 0.1 MV has acquired a kinetic energy of 0.1 MeV (or 100 keV). This is the operating principle of traditional diagnostic, industrial, and analytical X-ray tube (Fig. 1-7). The American physicist William D. Coolidge invented this type of X-ray tube in 1913.



Coolidge type stationary target X-ray tube.

An electron beam, usually on the order of milliamperes, is generated by heating the cathode. A voltage difference on the order of tens to hundreds of kilo volts across the tube accelerates the electrons to form a monoenergetic beam in which the kinetic energy of the electrons in electron volts is numerically equal to the voltage across the tube. The high-speed electrons are stopped by a high-atomic-numbered metal target that is embedded in the anode. Some of the kinetic energy in the electron beam is converted into X-rays (bremsstrahlung) when the electrons are suddenly stopped

In X-ray generators where the voltage is less than several hundred thousand volts,
the X-rays (photons) are emitted mainly at angles around 90° to the direction of the electron beam. A hole in the protective shielding that houses the X-ray tube allows
a useful X-ray beam to emerge from the shielded tube.

The X-rays that are produced in this manner have a continuous energy distribution that approaches a maximum energy equal to the kinetic energy of the electron that was stopped instantaneously and thus all of its kinetic energy was converted into an X-ray photon. If an electron were to be instantaneously stopped by the target, all of its kinetic energy would be converted into an X-ray photon.

This would represent the maximum-energy (or shortest-wavelength) photon possible with the given voltage across the tube. However, this maximum limit can only be approached, since no electron can be stopped instantaneously. The fact that the electrons are slowed down at different rates due to different ionization and excitation collisions leads to a continuous energy distribution up to the theoretical maximum energy that is determined only by the high voltage across the X-ray tube.

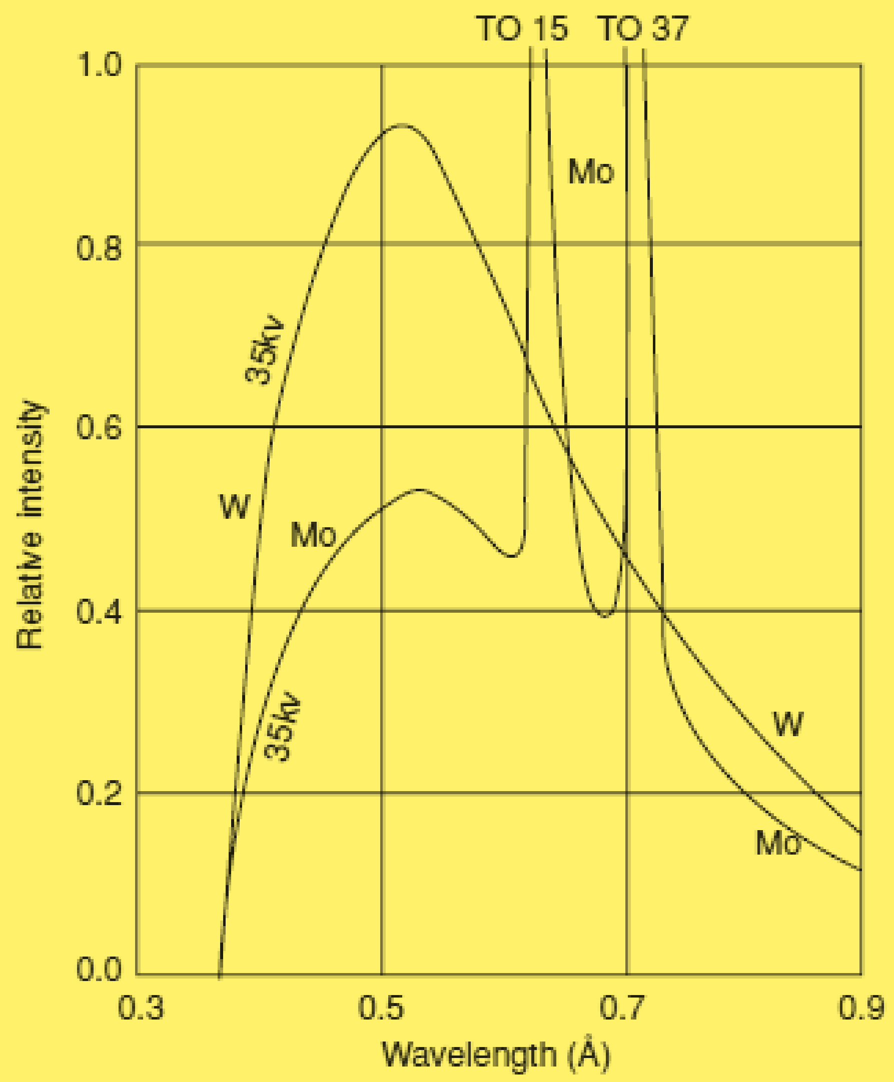


Figure 1-8. X-ray spectrum from a tungsten target (W) and from a molybdenum target (Mo) bombarded by electrons accelerated through 35 kV.

The theoretical maximum photon energy ($hc/\lambda_{minimum}$) *is equal to the electron's* kinetic energy when it strikes the target, which in turn is equal to potential energy of the electron before it is accelerated, *qV. Thus, the relationship between applied* voltage and the minimum wavelength, which is known as the *Duane-Hunt law, is*

$$qV = \frac{hc}{\lambda_m} \qquad (1\text{-}14)$$

$$\lambda_m = \frac{6.6 \times 10^{-34}\,\mathrm{J\cdot s} \times 3 \times 10^{8}\,\mathrm{m/s}}{1.6 \times 10^{-19}\,\mathrm{C} \times E\ \mathrm{eV}} \times 10^{10}\ \text{Å}/\mathrm{m}$$

$$\lambda_m = \frac{12,400}{E}\ \text{Å}. \qquad (1\text{-}15)$$

$$qV = \frac{hc}{\lambda_m}$$

$$\lambda_m = \frac{6.6 \times 10^{-34}\,\mathrm{J \cdot s} \times 3 \times 10^{8}\,\mathrm{m/s}}{1.6 \times 10^{-19}\,\mathrm{C} \times E\,\mathrm{eV}} \times 10^{10}\,\mathrm{\AA/m}$$

$$\lambda_m = \frac{12,400}{E}\,\mathrm{\AA}.$$

EXAMPLE

Calculate the wavelength of the 0.364-MeV photon from ^{131}I.

Solution

The wavelength of the 0.364-MeV photon from ^{131}I is

$$\lambda = 12,400 / E = 12,400 / (0.364x\,10^{6})$$

$$= 0.0341\ {}^{\circ}A.$$

1.2 Alpha Rays

1.2.1 Energy Relationship

Alpha rays are the least penetrating of the radiations. In air, even the most energetic alphas from radioactive substances travel only several centimeters, while in tissue, the range of alpha radiation is measured in micron (1µ $=10^{-4}$cm). The term range, in the case of alpha particles, may have two different definitions: mean range and extrapolated range. The difference between these two ranges can be seen in alpha particle absorption curve, Fig 1-8.